Strengthening masonry cross vaults damaged by geometric instability

Citation for published version:
Theodossopoulos, D, Sanderson, J & Scott, M 2015, 'Strengthening masonry cross vaults damaged by geometric instability', *Key Engineering Materials*, vol. 624, pp. 635-643.
https://doi.org/10.4028/www.scientific.net/KEM.624.635

Digital Object Identifier (DOI):
10.4028/www.scientific.net/KEM.624.635

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Key Engineering Materials

Key Engineering Materials Vol. 624 (2015) pp 635-643
© (2015) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/KEM.624.635

Strengthening masonry cross vaults damaged by geometric instability.

THEODOSSOPOULOS Dimitris[1, a *], SANDERSON James[2,b] and SCOTT Michael[2,c]

[1] ESALA, University of Edinburgh, 20 Chambers Street, Edinburgh EH1 1JZ, UK

[2] School of Engineering, University of Edinburgh, Edinburgh, UK

[a]d.theodossopoulos@ed.ac.uk,[b] j.a.sanderson@hotmail.co.uk , [c] michael_scotty3@hotmail.com

Keywords: Cross vaults, Gothic, FRP, abutment spread, Holyrood, rubble masonry.

Abstract. Cross vaults can be easily destabilised when their thrusts are not sufficiently contained by the stiffness of their lateral walls or systems of buttresses. A quarter-scale model from the aisles of Holyrood Abbey church in Edinburgh, which collapsed in 1768 due to excessive load from diaphragm walls that substituted the original roof trusses, demonstrated earlier the pattern of cracks that leads to failure under horizontal spread of supports. A recent model of this vault aimed to study the effects of applying Aramid fibre reinforcement against such failure exactly at the critical cracks, compared to other tests that studied arches or vaults under point load, reinforced continuously. The paper presents how the quality of certain areas of the fabric diverted failure from the longitudinal vertex merging with the detachment of the ribs, as originally observed. Moreover, the repair allowed the vault to resist 50% more spread of its supports, and failure occurred ultimately when new cracks formed in parallel to the repaired ones. The tests and repairs validate qualitative observations on crack patterns and failure of real cases and highlight the benefits and limitations when specific repairs are made instead of wholesome application of a reinforcing mesh at the extrados of vaults.

Introduction

Cross vaults are particularly strong structures on the condition that their thrusts are sufficiently contained by the stiffness of their lateral walls or systems of buttresses. Instability of this system can be caused by high lateral forces or earthquakes, failure of buttresses, unreasonable increase of the loads carried by the vault, historic defects locked in the fabric etc [1]. If deformation of the vault is detected early, it may be possible to repair effectively the vault against further instability. This work aims to study the effects of applying FRP reinforcement to strengthen such vaults under horizontal spread of their supports, which is usually how such actions can be simplified.

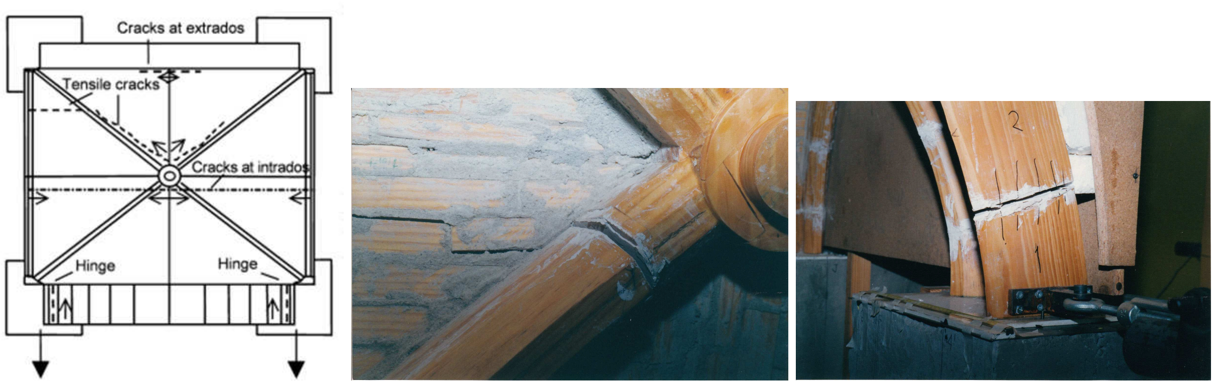


Figure 1. Crack pattern in a quarter-scale model of Holyrood Abbey church [2, 3]

Holyrood Abbey church in Edinburgh was chosen as a case study because the process of its collapse was well documented by W. Mylne in 1766. Most of its vaults collapsed in 1768 due to excessive load from diaphragm walls that John Douglas built to substitute the original roof trusses in 1760 [2]. The remaining aisles were simulated earlier by a quarter-scale model which was tested under service loads (dead load) and then brought to failure by lateral support movement [2, 3]. Those tests (Fig. 1) established a pattern that is known in practice and has been summarised qualitatively by J. Heyman [4]: the vault became unstable as a crack appeared at the intrados across the front of the longitudinal vertex, a hinge formed at the base of the nave arch and the back web detached along the back ribs and partially from the wall.

Nowadays, and according to the extent of the problem or the type of loads, such patterns are repaired with various forms of Fibre Reinforcement (FRP), which are reversible and can be designed to avoid altering the stiffness of the vaults excessively. Other benefits for stone vaulting include the facts that FRP is non-invasive, possesses high residual strength, is flexible in form but negligible in weight and in specific areas it responds well to cyclical (seismic) loads [5, 6]. Disadvantages include its relatively high cost, excessive dependence on the quality of in-situ application and lack of design codes [7, 8].

An experiment has been set up to study two valuable aspects in the failure and repair of masonry vaults: the application of FRP on very specific damaged areas, to reduce costs and effect of workmanship, and the effect of irregular rubble stonework to ultimate failure patterns. The vaults in Holyrood represent a quadripartite ribbed type made of oblong rubble masonry of average construction quality, which was probably plastered originally. The project aims to compare the behaviour and strength limits with the previous test of the model [2, 3] that had no reinforcement and managed to validate qualitative observations on crack patterns and failure [1, 4].

FRP repairs on vaults

Most of the experimental evidence available on repairs has been produced for single-curvature arches or vaults [9, 10, 11, 12, 13] and some less work has been done on more complex forms like cross-vaults or domes [14]. One of the most important parameters explored among others (like length & width, angle, type of loading, support conditions, type of fabric) is the positioning of FRP reinforcement (intrados, extrados, or exactly at the expected failure points) as it affects the collapse mechanism and ultimate failure load: the arch profile of a masonry vault is expected to fail by a 4-hinge mechanism and reinforcement provides ductility which can manifest at failure by debonding of the FRP along the adhesive joint or due to sliding of the blocks, tensile rupture of the FRP or crushing of the masonry blocks, according to where the neutral axis of the section moves.

Vaults in real conditions effectively exhibit planar 2D behaviour and they do not strictly split into arches [14], but cracks propagate within the shell. Tests on arches however are convenient as immediate failure can be studied once hinges has formed and discussion of a sample of such tests gives useful insight. In the tests by Valluzzi et al. [10], barrel vaults that were strengthened at the extrados experienced sudden collapse due to shear sliding between bricks and mortar in the joint closest to the springing of the vault. They showed that this can be prevented by placing fibres distributed properly in the springings. The ultimate load was higher than the tests on the intrados, which is further supported by Bricoli Bati & Rovero [9] (66% for the 1.25-cm-wide CFRP; 58% for the 2.5-cm-wide CFRP; 30% for the 5-cm-wide CFRP). Further studies of the postpeak phase of the load-displacement diagram [11] showed it was very similar to that of the unstrengthened arches.

Vaults that were strengthened at the intrados failed in a ductile manner due to detachment of the fibres near the point of loading [10], but did not collapse as the fibres helped to hold the bricks together. Other tests observed a hinge mechanism that formed at a load more than 12 times that of an unreinforced vault [12], but the usual 4-hinge mechanism sometimes occurs suddenly due to crushing of the blocks [8, 14], which is in many ways reminiscent of reinforced concrete: if the reinforcement bars fail, collapse is also sudden, without the warning signs of crack formation in the concrete. Study of the effect of the length [11] shows that increase of the FRP strips changes the collapse mechanism and increases progressively the ultimate load. Moreover, masonry crushing or shear failures reduce the postpeak phase of strengthened specimens (and their displacement capacity) by producing brittle mechanisms.

Many authors indicate that local reinforcement only is not a desirable option, as the other options improve strength significantly more. Valluzzi et al. [10] hypothesise that a possible solution to brittle failure in extrados applications could be to increase the surface area of FRP in the proximity of the springings, as this would also optimise the quantity of FRP used. However, care must be taken not to over-reinforce, as this has been seen to result in masonry crushing at the extremities of the fibres [7]. Despite the different collapse behaviours when reinforcing at the intrados and extrados, the collapse loads themselves were found to be quite similar [7]. It appears that the FRP does not have to span the whole of the intrados or extrados - a length of about 75% is sufficient. Alternatively, the use of steel cords provided higher strength compared to FRP [13] and the system the fibres to be anchored, but further research is required on its flexibility, durability and visual impact as it is a relatively new material.

Regarding other stability aspects, de Lorenzis et al [15] showed that the application of FRP reduces the lateral thrust transmitted to the piers substantially. The fibre can be placed either at the intrados spanning an angle centered at the crown, or at the extrados spanning two angles from the abutments towards the haunches (and anchored at the abutments).

The extent of the application of FRP is always prone to optimisation. For the half-brick vaults of the Town Hall in Assisi, CFRP bands were applied along the extrados of the groins only [16]. In order to avoid involving the abutments and to prevent debonding because of the unidirectional nature of CFRP sheets, anchorage of the sheets is recommended.

More complex behaviour and therefore repair strategy is expected for vaults and domes. Tests of a model brick cloister (groined) vaults [14], although the application of the load to the centre (keystone) does not have much correspondence to reality, it provides useful insight of the reaction of the vault to reinforcement. Two models were reinforced on 45% (grid) and 25% (parallel strips) of the extrados and failure occurred by crushing, at ultimate loads that were, respectively, 2.5 and 2.1 times that of the unreinforced model. The major restoration of the damaged vaults in St. Francis in Assisi [5, 6] highlights all the complexities when dealing with structures of high artistic value: the restoration of the load-bearing capacity occurred by attaching a grid of composite ribs (aramidic fibres combined with a timber nucleus) only at the extrados.

Holyrood and irregularities

The effect of irregularities or even the bond type of the masonry on structural behaviour has not been sufficiently studied. Holyrood represents many Scottish vaults that were not built in high craftsmanship to be visible (St Giles in Edinburgh, Jedburgh Abbey, Kirkwall Cathedral). The fabric is characterised by irregular joints and oblong blocks, both in terms of thickness and alignment (Fig. 2). The survey of the aisles that were conserved after the 1768 collapse show also occasional deviations from the intended design the vaults.

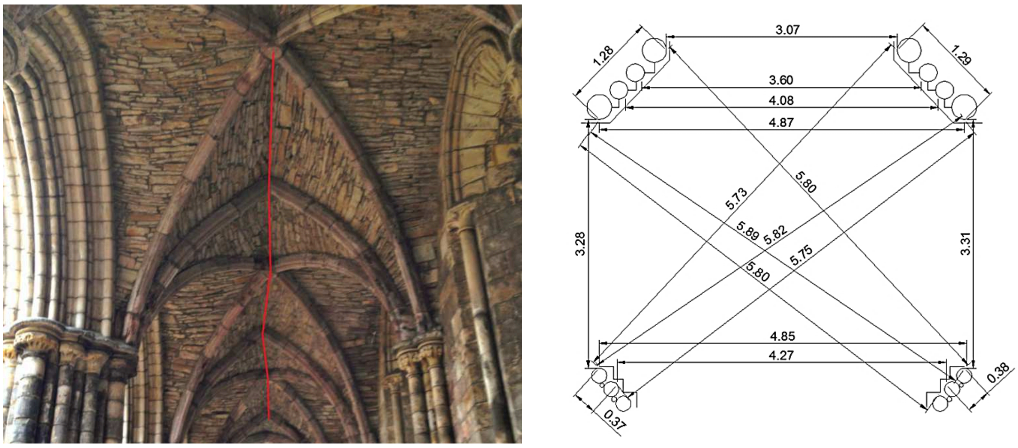
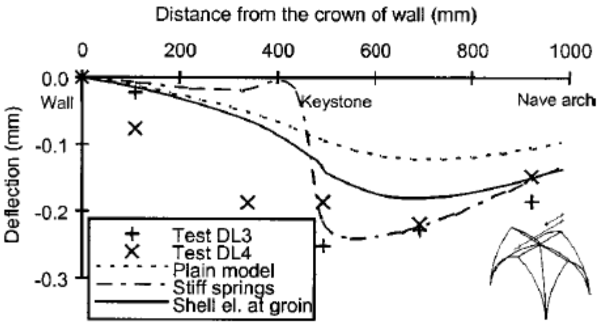


Figure 2. Irregular layout and masonry in Holyrood [17]

It is not certain how far these irregularities have affected the collapse, which may have been accelerated by insufficiently maintained flying buttresses and a probably not very well executed design of sexpartite vaults that was believed to roof the nave. The asymmetry of form and stiffness may have played a bigger role, when combined with insufficient constraints, as the case of equally deformed vaults that are contained by stiff piers and envelope shows (Blyth Priory, Selby Abbey).

Earlier work

The collapse of Holyrood Abbey church was well documented although the ultimate crack pattern was not recorded. The process of the collapse however represents well a typical failure, while the oblong blocks and the associated strong orthotropy are a very interesting parameter to study. A quarter-scale model of one of the aisle vaults was set up earlier, of 1275 x 945 mm plan dimensions. The model was tested to failure by spreading its two front supports, simulating the effect of the failure of the nave walls [2, 3]. The innovation compared to many other tests is that an almost complete structure is simulated, which includes many of the true conditions (like fully bonded ribs, spandrel fill, support conditions) and application of realistic load, like the vault's own weight as a uniformly applied load (DL) and the spread of the supports through deformation-controlled tests. The joints were tight and uniform and the oblong blocks were standardised into prismatic timber blocks.



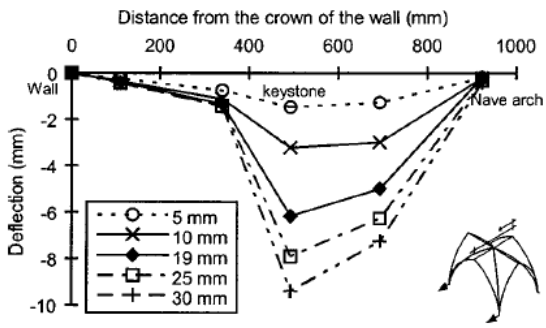


Figure 3. Deflection of the transverse ridge of a model vault from Holyrood Abbey under dead load (including FE analysis) and supports spread [2, 3]

The deformation of the main transverse vertex (Fig. 3), at both stages of the tests, showed a prominence of the deformation of the front portion, beyond the keystone. The stiffness of the nave arch becomes more significant in the support-spread tests: it reduces deflection in the arch's immediate area but the entire front portion of the vault follows the rotation of the stiff plane the arch creates, causing the excessive deformation and eventually detachment of this area from the rest (Fig. 1). The crack pattern (Fig. 1) is relevant to that of many vaults, and its initial stages often appear in service conditions in aisle vaults (especially the crack on the sides of the longitudinal vertex). Failure occurred at 30mm spread (or 1/32 of the span), in a 3 hinge-line mode, although the vault could be spread further to 90mm till a catastrophic collapse occurred.

Experimental set-up

The Holyrood model was rebuilt recently with the aim to test how far FRP repairs can extend the service life of the vault after significant cracks had formed [17]. Compared to other approaches [5, 14, 16] fully epoxy-bonded aramidic fibre reinforcement was applied only locally on the surfaces that have cracked. The test aims to demonstrate how effective such an intervention would be, bearing in mind the artistic values the stonework may show at its intrados and the very rugged, often undressed, extrados surface, which is not always accessible. Moreover, the deformation of the vault was monitored with a Leica TPS1200 total station that produced 3D coordinates of selected points.

Prior to the application of dead load, the original (unloaded) shape of the model was determined by measuring the location of these points, selected along the top of both ridges, across the front webs, and along the top of the nave arch. A distributed dead load was then applied in the form of steel and lead weights distributed symmetrically across the extrados of the vault, held in position using steel brackets, giving a total load on the vault extrados of 176 kg or 1 kN/m^2 (the previous tests had 330 kg or 1.9 kN/m^2 applied [2]).

Following the appearance of cracks, repairs were carried out to both the intrados and extrados using FRP bonded with epoxy. The repair materials were applied in four stages. First, in order to prepare the rough surface of the webs, fill cracks, and provide a level surface, an epoxy 'putty' was applied to the repair zones; the putty was made by mixing epoxy with sawdust in order to increase the stiffness. Once this had cured, a layer of epoxy was applied, followed by the FRP fabric, and finally a saturation layer of epoxy. The FRP fabric chosen was a lightweight, flat-braid aramid FRP, with a 45° width of 32 mm. Apart from its lightness (300 g/m^2), its flexibility also enables high conformity to the uneven shape of the vault without buckling the fibres. The epoxy used was made up of an epoxy laminating resin, a slow hardening agent, and fumed silica thixotropic powder. The low viscosity of this epoxy allows the FRP to be fully wetted with a low likelihood of air pockets creating bubbles, whilst its low weight and high cured strength are also beneficial.

Failure of a model cross vault due to supports spread

The tests will be discussed at the main stages of supports spread and their repair, and the crack patterns are summarised in Fig. 4. After the first spread of 2 mm, small hairline cracks appeared: on the extrados between the nave arch and webs; along the diagonal rib between the longitudinal ridge and diagonal rib on the front left hand side; and just in front of the longitudinal ridge on the left hand side. The cracks between nave arch and webs were also visible on the intrados, but otherwise no new intrados cracks had appeared. At a spread of 4 mm, a significant transverse crack opened up between the longitudinal ridge and diagonal rib on the front left hand side, extending downwards roughly parallel to the diagonal rib. By the time the supports had been spread to 6 mm, this crack had expanded further, whilst the lower portion of the web had dropped by 2 mm. It is notable that the crack appeared to have originated from where two continuous (aligned) vertical joints. It was decided that in order to avoid premature failure of the vault, these cracks should be repaired at the intrados with FRP and epoxy before spreading the front supports any further.

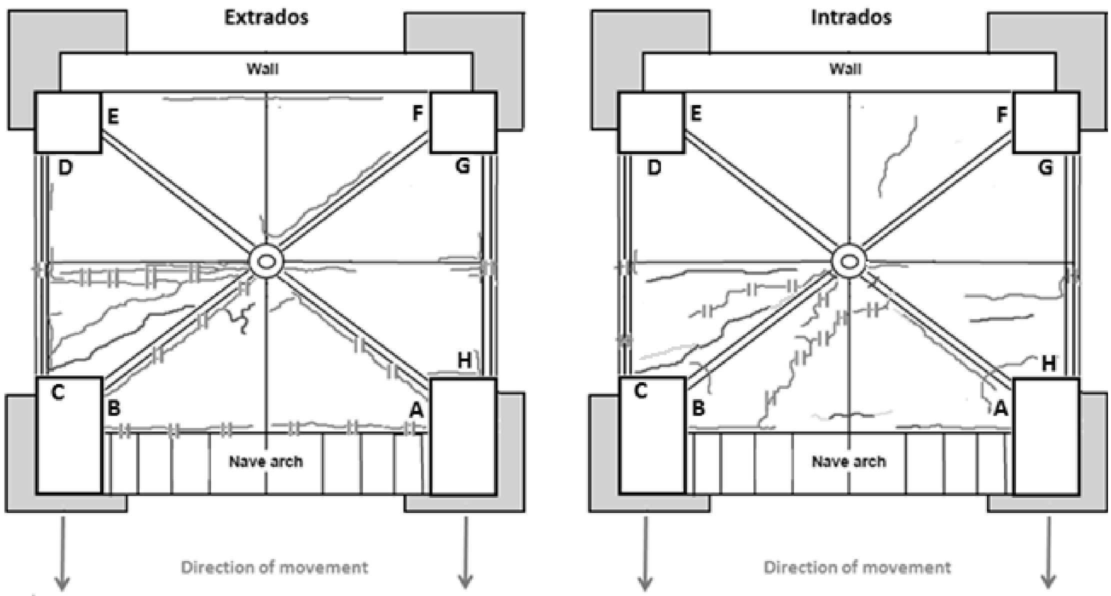


Figure 4. Location of cracks on extrados and intrados and repairs [17]


Figure 5. FRP repairs to the extrados and intrados of the vault [17]

Repair and ultimate failure

By 6 mm, the other smaller extrados cracks which had opened up after 2 mm had generally extended significantly in length without widening. A crack had also appeared in the intrados just in front of the longitudinal ridge on the right hand side. As can be seen in Fig. 6, the majority of the cracks could be found at the extrados on the front left side of the vault, with several cracks parallel to the longitudinal ridge as well as the large diagonal crack leading into the transverse arch. Cracks had also appeared at the extrados along both diagonal ribs at the front of the model, and at the joint between the nave arch and web at both the extrados and intrados.


Figure 6. New diagonal crack at the front left extrados at 22 mm spread and at intrados

Following the repair work, further spreading was carried out, initially to 8 mm. A crack opened up at the intrados towards the back of the vault, and the top of the back wall of the vault also began to separate from the web at the extrados (Fig. 4). A short crack also appeared at the intrados near the keystone at the front of the vault. After 10 mm, this intrados crack had propagated to the nave arch, and other pre-existing cracks near the keystone had become more pronounced. However it was noticeable that the repaired crack had not expanded any further, with the FRP apparently proving effective at holding it together. At 15 mm spread, the nave arch became almost completely detached from the web at the extrados, and a new extrados crack appeared along the diagonal rib at the back of the model. Several smaller cracks also appeared, mostly around the ribs and ridges.

At 18 mm, the crack along the back wall was also increasing in length, although still a hairline one. On the extrados, new cracks appeared in the both the back and front half. There are a number of new cracks at the intrados, mostly confined to the front half. The general crack pattern is still rather asymmetrical, with most cracks occurring in the front left part of the model. By that stage, many of the pre-existing cracks had also opened up significantly, so further fibre repairs were necessary. This was particularly necessary at the joint between the web and nave arch (Fig. 6), which was in danger of complete separation, almost certainly causing collapse. The cracks on the front left were also much larger than those on elsewhere; indeed almost all of the FRP repairs were located in this quadrant of the vault, as elsewhere the cracks were not large enough to require repair.

Following these repairs, at a 22 mm spread a significant new crack appeared parallel to the large diagonal crack, already repaired at 6 mm (Fig. 6). This new crack also protruded right through the web joints, being clearly visible at both the extrados and intrados. Other smaller cracks also appeared at the intrados parallel to the longitudinal ridge. However the repairs carried out at 18 mm again proved effective at preventing any further expansion of these cracks.

At 25 mm spread there were some crack extensions in the intrados, and the large crack which had appeared at 22 mm continued to widen, along with other unrepaired cracks at the front of the intrados and at the back wall on the extrados. From 25 mm spread onwards, no new cracks were observed, but the pre-existing cracks expanded further. At a spread of 31 mm, the vault failed, with a large portion of the web in front of the longitudinal rib detaching completely and collapsing.

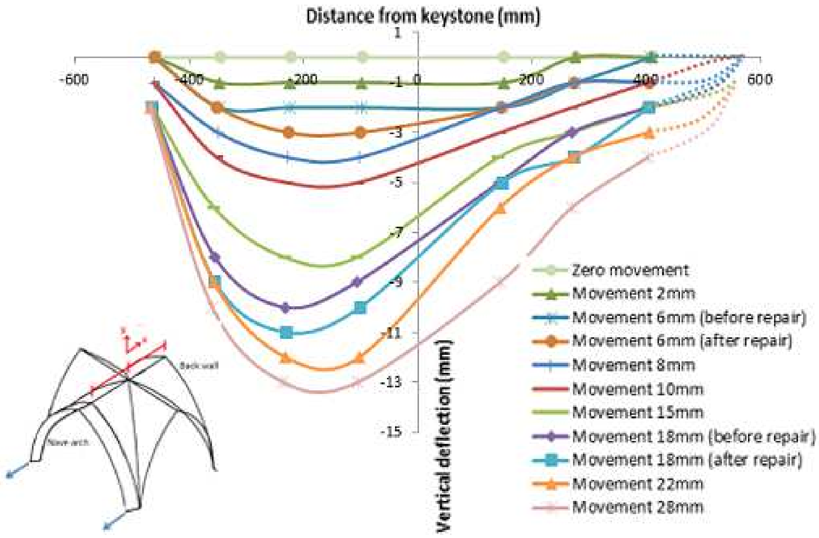


Figure 7. Deflection of the transverse ridge (nave arch on the left, wall on the right) [17]

The deflection of the transverse ridge (Fig. 7) shows a clear trend, with the ridge gradually deflecting downwards as the front supports are spread. The front half of the ridge has the greatest deflections (up to 13 mm at points 111 and 112), with the ridge gradually sloping downwards from the back wall towards the front. Comparison with the previous test (Fig. 3) shows the deflection is higher (max 10mm at 30mm spread), which is expected from the lower stiffness due to the workmanship of the fabric in this test.

Following the failure of the vault at 31 mm, the front supports were spread further in order to observe where the next collapse would occur. The supports were spread up to a total of 74 mm, at which point a large section of the web next to the back wall fell inwards. During this spreading, the two intrados cracks parallel to the longitudinal ridge at the front right of the vault became increasingly pronounced; however failure of this section did not appear to be imminent.

Discussion and conclusions

The tests on a complete cross vault confirmed earlier observations of a shell behaviour [2, 3], rather than split of the vault into arches [14] as the cracks clearly propagated in various patterns through the shell. The different craftsmanship of the model produced thicker horizontal joints and some continuous vertical ones. The vault in this test followed a similar pattern as previously (Fig 1, 3, 7) but these areas of weakness caused the cracks to spread in broader zones (Fig. 4). As a result, the vault was repaired earlier than expected (18mm instead of 30mm when the earlier model failed), but its service life extended to 31mm (+72%). The beneficial effect of the repair also shows that interestingly the vault fails eventually at the same spread, indicating the limits of such form.

No crushing of blocks was observed (intrados reinforcement), but sliding from the spandrels could be the effect of FRP at extrados [9, 10, 11] and FRP at springing may have been beneficial. Some expected reduction of thrust [15] may have caused occasionally the retraction of the vertex after a repair, before further spread caused forward movement again. Finally, the effect of length and anchorage [11] was less of a problem as repairs were exactly along the crack, but the length of some strips may have caused some of the diffusion of brittle mechanisms.

Acknowledgments

The authors are indebted to Messrs Malcolm Cruickshank and Paul Diamond, at the Architecture Workshop in ESALA, and Dr. Tim Stratford, at the School of Engineering, for invaluable support in the fabrication and repair of the model.

References

[1] D Theodossopoulos, BP Sinha. Structural Safety and Failure Modes in Gothic Vaulting Systems. 8th International Seminar on Structural Masonry, Istanbul, November 2008.

[2] D Theodossopoulos, BP Sinha, AS Usmani. "Case Study of the Failure of a Cross Vault: Church of Holyrood Abbey" J. Archit. Engrg, ASCE, vol. 9 (3), 2003, 109-117.

[3] D Theodossopoulos, BP Sinha, AS Usmani, AJ Macdonald. Assessment of the structural response of masonry cross vaults. Blackwell Science Ltd. Strain 38 (2002), p. 119-127

[4] J. Heyman. The Stone Skeleton. Cambridge University Press; Cambridge, 1995.

[5] G Croci, A Viskovic, New technologies to protect historic buildings from seismic risk. Int. Conf. Seismic Performance of Traditional Buildings, Istanbul, 2000.

[6] A Balsamo, U Battista, A Herzalla, A Viskovic The use of aramidic fibres to improve the structural behaviour of masonry structures under seismic actions. Proc. Int. Congress Archi. 2000.

[7] PB Lourenço, J Poças Martins. Strengthening of the architectural heritage with composite materials. 2001. University of Minho, Guimarães

[8] Y. Tao, JF Chen, T.J. Stratford. Repair of a Model Masonry Arch Bridge using FRP. Advanced Composites in Construction (ACIC) conference, Edinburgh 2009.

[9] S. Briccoli Bati, L. Rovero, Towards a methodology for estimating strength and collapse mechanism in masonry arches strengthened with Fibre Reinforced Polymer applied on external surfaces, Materials and Structures, RILEM, Vol. 41(8) 2008, 1291-1306

[10] Valluzzi, M., Valdemarca, M., and Modena, C. (2001). Behaviour of Brick Masonry Vaults Strengthened by FRP Laminates. Jnl. Comp. for Construction, August 2001. p. 163-169.

[11] L Rovero, F Focacci, G Stipo. Structural behavior of arch models strengthened using fiber-reinforced polymer strips of different lengths. J. Comp. for Construction, ASCE, 17(2), 2013.

[12] R Di Marco, P Faccio, P Foraboschi, E Siviero. Volte in muratura rinforzate con FRP. Costruire in laterizio, 69, 66–71, 1999.

[13] A. Borri, P. Casadei, G. Castori, J. Hammond. Strengthening of Brick Masonry Arches with Externally Bonded Steel Reinforced Composites. Jnl. Comp. for Construction, ASCE, 13(6), 2009, 468-475

[14] P. Foraboschi. 2004. Strengthening of Masonry Arches with Fiber-Reinforced Polymer Strips. Jnl. Comp. for Construction, ASCE, 8(3), 2004, 191-202.

[15] De Lorenzis, Dimitri, La Tegola. Reduction of the lateral thrust of masonry arches and vaults with FRP composites. Construction and Building Materials, 21 (2007) 1415–1430

[16] A Borri, M Corradi, A Vignoli, Seismic Upgrading of Masonry Structures with FRP. Proc. 7th Int. Conf. Inspection, Appraisal, Repairs & Maintenance of Bldgs & Structures, Nottingham Trent University, Nottingham 2004, pp. 43-54

[17] J Sanderson, M Scott. Investigation into the use of FRP as a repair material for Gothic cross vaults. Dissertation, MEng in Civil Engineering, University of Edinburgh 2014